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RECENT DEVELOPMENTS IN THE DYNAMICS OF WIND-EROSION

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Introduction

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Those particles of the Earth's land-surface that are in contact with the atmosphere are at the mercy of two powerful natural forces, resulting from water- and air-flow. The story a single soil-grain could tell of its travels would surpass that of Marco Polo. It is unfortunate that one cannot "get the story" and thus answer many questions that are in the minds of those who wish to explain and control its behavior.

The transport of granular material by fluids has been a subject of intense interest, especially in connection with flowing water. A great number of investigations have been made, both in the laboratory and in streams, on the effects of water-erosion and the underlying mechanisms of the movement of debris. As a result, at least for some phases of the process, explanations and empirical rules have been developed.

When one turns to the problem of the transport of soil by wind, a much less satisfactory situation is found. Within the last decade, a pressing need has arisen in the United States for an understanding of the fundamental principles of wind-erosion due to the severe movement of soil in the Great Plains region. The phenomenon of the "dust-storm" has become familiar, even in the City of Washington--2,000 miles distant from the region in which the particles were carried aloft.

To the soil conservationist fell the responsibility for developing methods of checking this destruction of vast areas of valuable land. The necessity of doing something quickly to alleviate a suddenly critical situation brought about an almost "panicky" search for a solution.

The most obvious way of evaluating proposed control-methods lay in trying them in the field. A large number of such investigations have been conducted to determine the defectiveness of various land-use methods and the effectiveness of corrective measures. Experiments of this type are of primary importance; however, they are handicapped by dependence on the whim of the weather, the often objectionable length of time needed to obtain data, and in many instances the prohibitively large cost. The fact that a control-method recommended in one region may not succeed in another further restricts the value of the field-studies.

To these difficulties must be added the inherent complexity of the problem. In Table 1 some of the variables that play a greater or lesser part and some of the surface-effects that result are listed.

Table 1

Wind	Surface	Topography	Soil	Surface-effects
Speed	Roughness	Flat	Texture	Removal
Direction	Cover	Undulating	Structure	Deposition
Structure	Obstructions	Broken	Organic content	Surface-markings
Temperature	Temperatures		Moisture-content	Dune-formation
Humidity			Soil-binders	
Burden carried				

The number of situations that can be set up by making combinations of the variables listed in Table 1 is seen to be very large. The following problems are of basic importance and are, therefore, the ones upon which research has been concentrated:

(a) The mechanism of lifting the soil from surfaces and the mechanism of transportation and deposition of particles

(b) The dependence of the amount of soil blown on the velocity and turbulent structure of wind

(c) The effect of the soil-surface and suspended soil on the velocity-distribution and structure of wind

(d) The distribution of transported soil-particles above the surface

(e) The effectiveness of obstacles of different kinds in preventing soil-blowing

(f) The mechanism underlying the formation of dunes and drifts, and methods of reclaiming such areas

The problems of the soil conservationist in fighting wind-erosion are similar to those encountered by the pioneers in the development of aircraft. The modern airplane has been made possible to a large extent by experimentation using a suitably directed, artificially produced wind. The device used in this research is known as a wind-tunnel.

In the following sections, the wind-erosion process will be hastily reviewed and the recent introduction of the soil-blowing tunnel, as an aid in predicting the behavior of exposed soil-surfaces to wind, will be discussed.

(1) The wind-erosion process--General remarks

The wind--In the practical problem of combating wind-erosion, the interaction between the prime mover--air--and exposed soil-surfaces of diverse character, must be understood before effective control-methods can be developed.

An air-stream, moving over a surface, can be described by the variation of its mean velocity and its turbulent structure with height above the surface. The layer of air, extending roughly to a height of the tallest obstruction in the field, is of major importance for nothing can be done purposely to influence the transport of particles once they exceed this height.

When turbulent unladen air flows over an unobstructed flat surface, the variation of the mean velocity of motion, u, parallel to the surface, with the height, z, is well represented by Prandtl's extension to the atmosphere of von Kármán's logarithmic relation

$$u = 5.75\sqrt{\tau/\rho}\ \log_{10}(z/k) \qquad (1)$$

where τ is the friction per unit area acting on the surface, ρ is the air density, and k is a roughness factor, usually taken as 1/33 to 1/30 of the average diameter of the surface-elements.

In Figure 1 velocity-profiles obtained for air flowing in an open channel and a rectangular working section of a wind-tunnel are compared with the profile of a natural wind, calculated from (1), with k corresponding to a fixed sand-surface of 0.01-inch diameter grains.

The effect of various types of ground-surfaces on the velocity-distribution, as measured by Chepil and Milne with a portable field-tunnel, are shown in Figure 2.

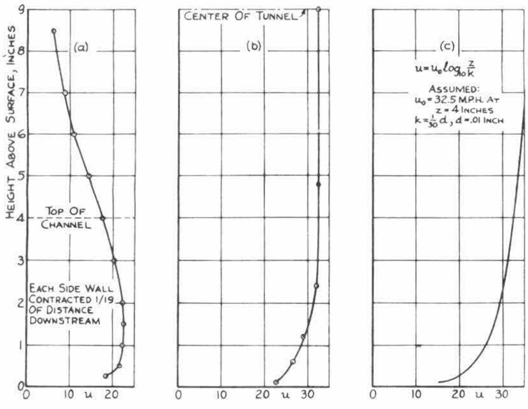

Fig. 1--Velocity-profiles obtained in (a) open-top channel with contracted side walls, (b) rectangular working section of California Institute of Technology soil-blowing tunnel, and (c) calculated from logarithmic relation

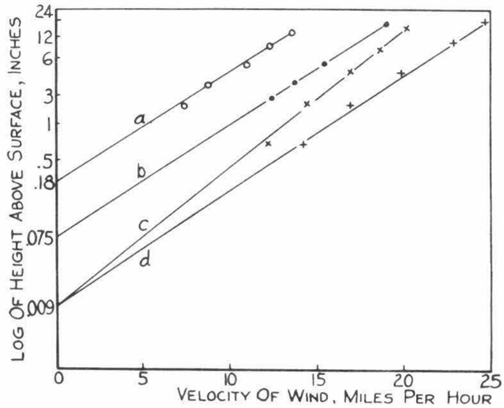

Fig. 2--Wind-velocity gradients, obtained over various types of ground-surfaces in a portable soil-blowing tunnel: (a) Level ground-surface covered with a growth of bromegrass about six inches high; (b) rather thin, irregular wheat stubble, about seven inches high; (c) smooth, level, bare ground; (d) same as (c) with wind-velocity increased (Measurements of W. S. Chepil and R. A. Milne)

Turbulence in the wind--In expression (1), for the variation of velocity with height, it is important to notice that it is an expression for the mean velocity of motion. The actual wind is turbulent, that is, upon the mean velocity, measured with an averaging instrument, such as a pitot-static tube, there are superimposed velocity-fluctuations, due to the existence of eddies in the flow. G. I. Taylor has defined turbulence as follows: "Turbulence is an irregular motion which in general makes its appearance in fluids, gaseous or liquid, when they flow past solid surfaces or even when neighboring streams of the same fluid flow past or over one another."

Further, to paraphrase von Kármán: "Common language, even in technical papers, uses the term turbulence in a rather indefinite way, including in it for instance, vortex motion in general. The scientific term turbulence implies irregular fluctuations, governed by laws of some statistical equilibrium. To be sure, turbulence may be originated by vortices resulting from the flow through a honeycomb; but we call such a motion turbulent only if the regular pattern, because of the intermingling of a great number of vortices, disappears, as happens further downstream from the honeycomb. Similarly, vortices produced by obstacles at the ground contribute essentially to atmospheric turbulence, but also in this case we restrict the term turbulence to the statistical phenomenon of the mass-exchange and keep this case apart from other conceptions, such as individual vortices (tornadoes, vortex sheets, etc.) or regular atmospheric waves."

Turbulence is the subject of intense investigation in fluid mechanics at the present time. The results, thus far obtained, indicate that for a turbulent flow, in which the velocity-fluctuations in the three orthogonal directions (x,y,z) are denoted by (u',v',w') can be described: (a) By the turbulence-level (or intensity), whose value is given by the ratios of the root mean square of the velocity-fluctuations $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$, $\sqrt{\overline{w'^2}}$ to the mean velocity u; and (b) by the scale of the correlation-function measured, for example, by the distance between two points, for which the correlation-function of a certain velocity-component has a given value.

Assume that the velocity-fluctuation u' has the values u'_1 and u'_2 at two points P_1 and P_2, then the ratio $\overline{u'_1 u'_2} \big/ \sqrt{\overline{u'^2_1}} \sqrt{\overline{u'^2_2}}$ determines the correlation-function for u'. The distance at which the function drops to a certain value, say one-half, is a measure of the scale of the correlation.

The turbulence-level gives a measure of the intensity of the velocity-fluctuations, and the scale of the correlation-function a measure of the physical size of the eddies. Figure 3 is an example of the intensity of the velocity-fluctuations in a wind-tunnel, and Figure 4, an analysis of wind-structure near the ground.

One more modern fundamental concept developed in connection with turbulent flow needs mentioning. That is the concept of the turbulence exchange-coefficient or kinematic eddy-viscosity ϵ. In the case of laminar flow, the interaction between adjacent layers is made evident by molecular friction and the shearing stress τ is given by the product of the kinematic viscosity μ and the gradient of the velocity (du/dz), that is, $\tau = \mu$ (du/dz).

When the flow becomes turbulent, in addition to molecular interchange, lumps of fluid are transported from one layer to another, and the shearing stress is given by the momentum transferred through unit-area in unit-time, or $\tau = \epsilon \dfrac{d}{dz} (\rho u)$.

The exchange-coefficient ϵ in addition to acting as a viscosity-coefficient, also gives an indication of the range of penetration of the turbulent eddies that serve as carriers of transferable quantities such as heat, momentum, and soil-particles.

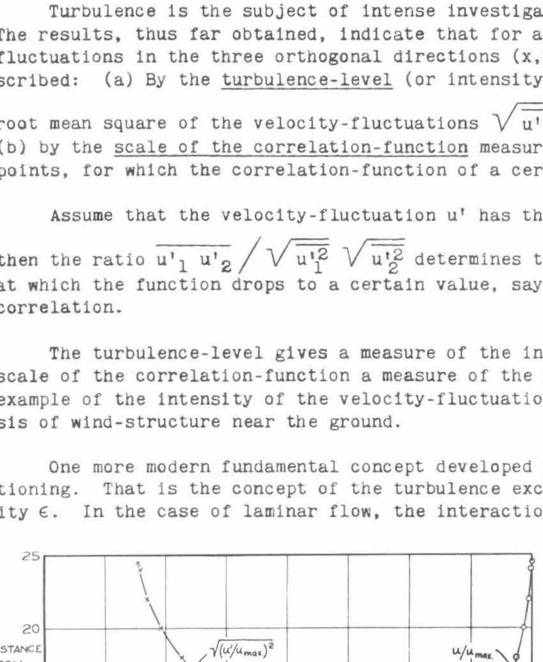

Fig. 3--Distribution of mean velocity and velocity-fluctuations in wind-tunnel of rectangular cross-section with large aspect ratio (Measurements of Wattendorf and Knoblock, California Institute of Technology)

Obstructions--Consider, for example, an unladen wind that starts over a sandy plain with a velocity-distribution given by (1) and possessing a definite turbulent

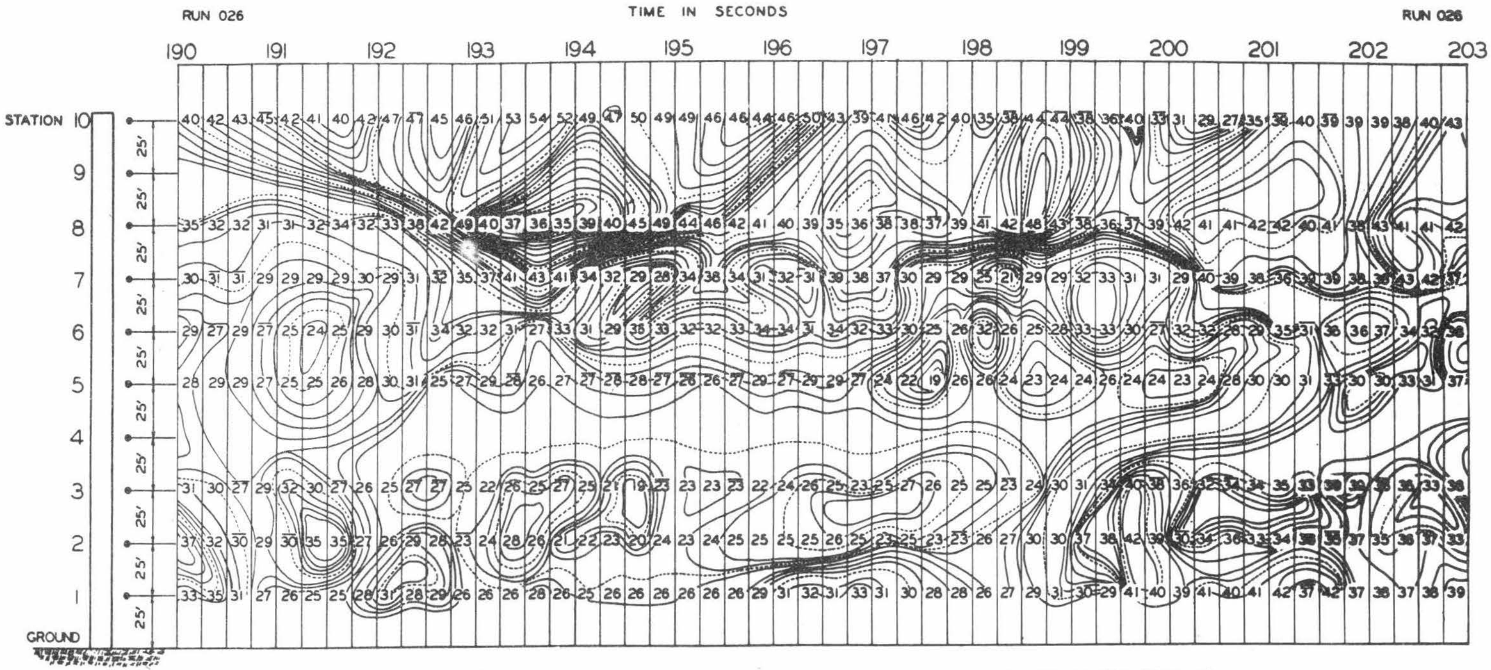

Fig. 4--Analysis of wind-structure near ground showing lines of equal velocity as function of height and time (Measurements of R. H. Sherlock and M. B. Stout)

structure. As it moves across a typical countryside, it encounters surfaces of varying roughness and obstructions of different kinds that alter and distort its velocity-distribution and vary its turbulent structure. For simplification, obstructions will be understood to denote localized obstacles that influence the wind as opposed to cumulative effects of large areas, covered more or less uniformly with similar obstacles. The latter can be thought of as surfaces of macroscopic roughness. Under this classification the following are obstructions: Windbreaks, fences, terraces, embankments, buildings, and crop-strips.

It is convenient at this point to discuss briefly an important law of fluid flow discovered by O. Reynolds. It states that, for flows around two geometrically similar bodies to be dynamically similar, the ratio, known as Reynolds Number

$$(\rho U \ell / \mu) = Re \tag{2}$$

must have the same value. In the above relation, ρ is the density of the fluid, U is the velocity of flow, ℓ is a characteristic length of the body, and μ is the viscosity of the fluid.

Although the Reynolds Number was originally developed for the consideration of flow of fluids around solid bodies, its importance has extended into all phases of fluid mechanics. The Reynolds Number and turbulence have been called by H. L. Dryden the companions that determine the character of fluid flow.

The natural wind, in flowing over obstructions of different types on the ground, can, therefore, be expected to be influenced by their size and shape. Windbreaks and certain other obstacles add another factor to affect the flow-pattern, in that they possess porosity.

Soil--The soil adds many factors to the problem, due to its varied physical nature. It is made up of solid, liquid, and gaseous components. The effect of the last two components on the erodability of soil by wind is largely unknown.

The solid portion of soil is made up of inorganic and organic matter. The inorganic part is composed of mineral particles, which are classified, according to size, into three principal groups, called sand, silt, and clay. The particle-sizes have been arbitrarily fixed at diameters of 2 to 0.05 mm for sand, 0.05 to 0.002 mm for silt, and less than 0.002 mm for clay.

The texture of soil is determined by the proportion of the particles of different size that a sample contains. Figure 5 shows the distribution of particle-size in a sample taken from a barchan dune near the Salton Sea in California, and Figure 6, the per cent of sand, silt, and clay in soils of various texture.

Individual grains of soil determine its texture and their arrangement its structure. Some of the types of structure are single grain, crumb, granular, fragmentary, mulch, prismatic, shot, angular, nut, etc.

The susceptibility of unprotected soil to blowing is dependent to a large extent on its texture and structure. Since these two physical characteristics change in a soil-profile, it is possible that an area have varying rates of erosion as the surface is lowered.

An important aerodynamic quantity of an individual grain is its terminal velocity of fall through air. Grains differ from one another, not only in size and composition, but also in shape, which affects their settling velocity. The shapes of Nevada white-sand particles, taken from a sample having a geometric mean sieve diameter of 0.47 mm, are shown in Figure 7. It is usual practice to consider a sample as made up of spherical grains, whose rate of fall is equivalent to the average rate of fall of the actual grains. The settling velocity of quartz spheres in air and water is plotted in Figure 8.

(2) The initiation of the movement of soil

The wind-erosion process consists, in general, of three distinct phases--initiation of the movement of soil-particles, their transport, and their deposition. The mechanisms underlying the phases are not as yet clearly understood; however, on the basis of investigations thus far made and analogies drawn from the transport of debris by liquids, a number of hypotheses have been advanced.

When this section was being planned, it was intended to summarize the various theories advanced in connection with liquids for the initiation of soil-movement. However, upon reading

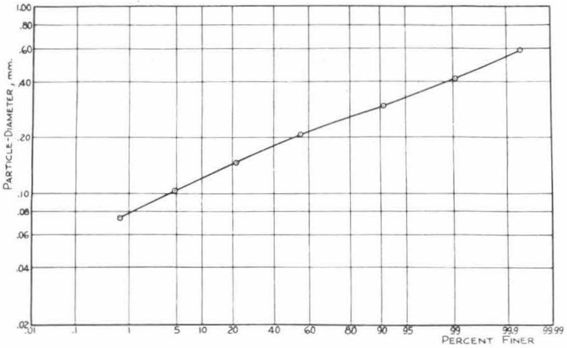

Fig. 5--Sand-particle-size distribution in sample taken from barchan dune, near the Salton Sea in California

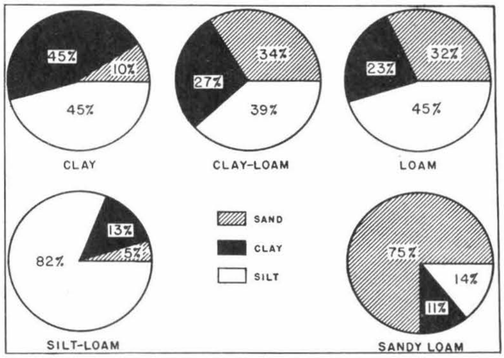

Fig. 6--Per cent of sand, silt, and clay in soils of various textures (According to Rice and Alexander)

the most recent discussion of the problem by H. A. Einstein, it was felt that only a picture of the forces acting in the process was in order. Einstein makes the statement:

"Attempts have been made in the past to derive an expression for the initial movement that is governed by certain definite critical conditions to be used as the first step toward the solution of the transport-problem. In interpreting the results of many experiments on bed-load movement, and in comparing them with those obtained by other experimenters the writer has concluded that a distinct condition for the beginning of transport does not seem to exist. It is just as impossible to determine the limit of initial movement as to determine the maximum possible flood of a river."

This statement requires further verification, for the critical factors controlling the initiation of movement of soil-particles are of great importance in the prevention of erosion by wind.

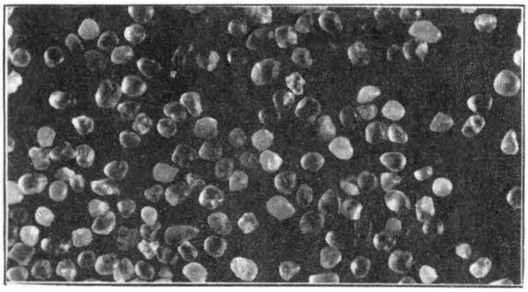

Fig.7--Photomicrograph of Nevada white sand of 0.47-mm geometric mean sieve diameter, magnified 5 diameters

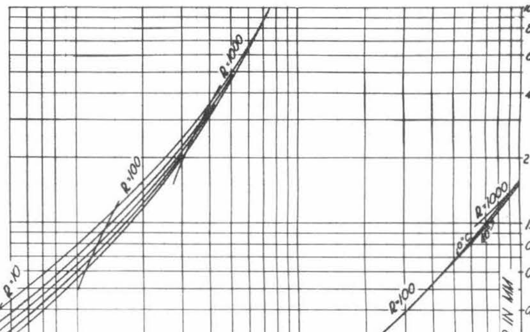
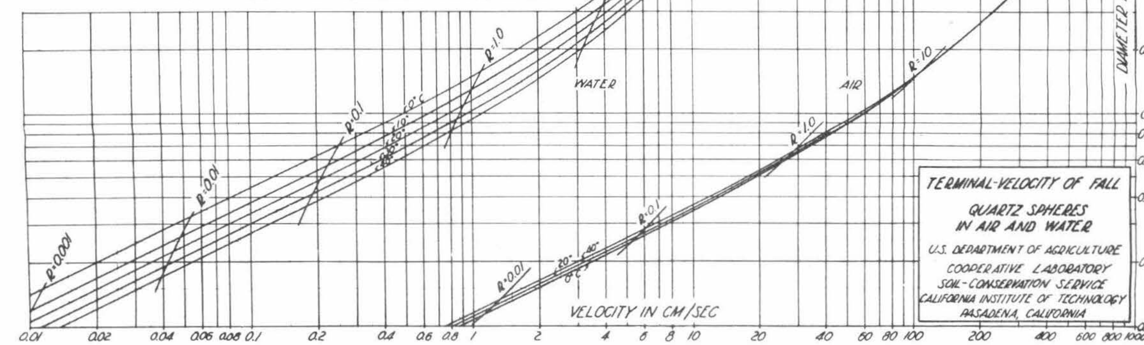

Fig. 8--Settling velocity of quartz spheres in air and water (Prepared by H. Rouse)

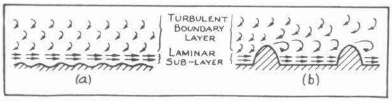

Fig. 9--Schematic diagram showing laminar sub-layer and roughness (a) not affecting and (b) affecting the main turbulent flow

A closer study of the nature of fluid flow near a surface shows that the relation (1) for the distribution of mean velocity holds satisfactorily in a fully developed turbulent flow. When a fluid moves over a surface the boundary-layer has been found to consist of two regions of flow. Very close to the surface the motion is laminar and the region is known as the laminar sub-layer (Fig. 9). The main turbulent region above is not affected by the surface-roughness until the roughness-elements emerge through the laminar sub-layer. S. Goldstein found that roughness elements of height d would be within the laminar sub-layer as long as

$$d\sqrt{\tau/\rho}/\nu \leq Re_c \leq 4 \tag{3}$$

where ν is the kinematic viscosity of the fluid and Re_c is the critical Reynolds Number.

Particles making up the surface are, therefore, acted upon by forces according to the type of flow about them. Thus in the laminar sub-layer viscous stresses predominate, in the transition-region from laminar to turbulent flow, viscous and Reynolds stresses are of the same order

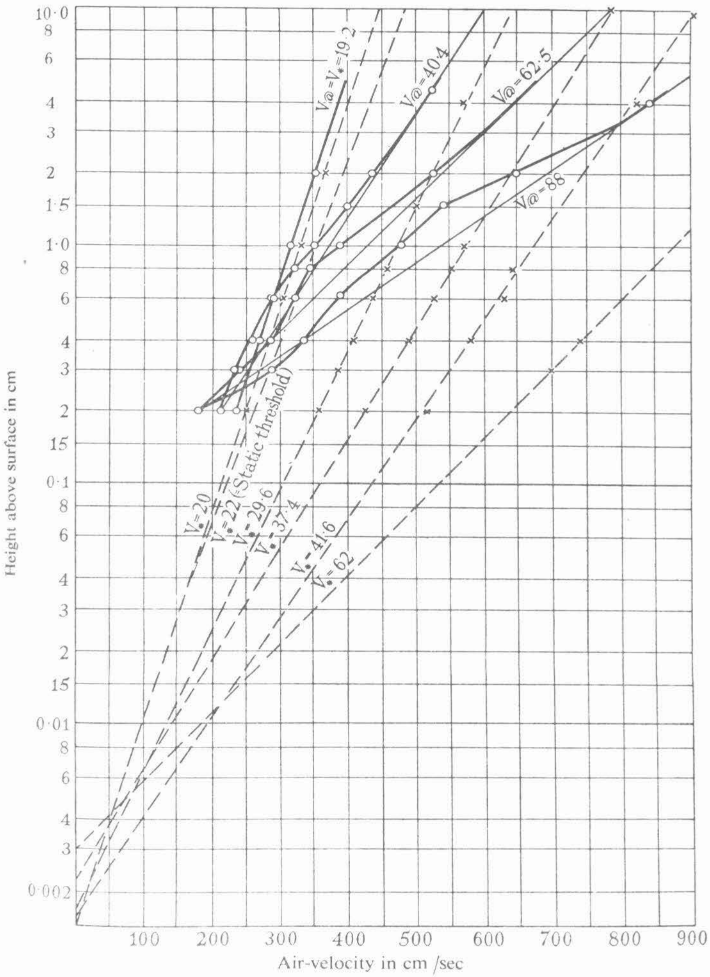

Fig. 10--Normal wind-velocity distributions; dotted lines refer to flow without sand-movement and heavy continuous lines to flow during sand-movement (Measurements of R. A. Bagnold)

of magnitude, and in the fully turbulent region only Reynolds stresses need be considered.

P. Nemenyi classifies the mechanical forces acting on an individual grain as follows:

(a) Forces exerted upon the grain-surfaces by the fluid (F_f)
(b) Terrestrial gravity--weight of grain (F_w)
(c) Surface-forces both normal and tangential exerted by other grains (pressure-, friction-, and impact-forces) except those caused by mass-attraction (gravitation) between grains (F_s)
(d) Forces exerted by other grains in consequence of mass-attraction--cohesional influences (F_c)
(e) Inertia forces (F_i)

Since, in connection with wind-erosion, little is known of the effect of the above forces, it is necessary to know under what conditions the conclusions obtained with liquids can be applied. Nemenyi states that the simplest assumption for the existence of dynamic similarity is that the ratios F_f/F_i, F_w/F_i, F_s/F_i, and F_c/F_i should be the same for corresponding grains.

A number of semi-empirical formulas have been developed for the determination of the critical conditions under which particles begin to move. The starting point in the derivation of the formulas is the equilibrium of an individual particle. If a particle were spherical in shape and isolated, the problem would be quite simple; however, the fact that shape and size vary and that each particle in a bed is influenced by its neighbors, has made it necessary, thus far, to introduce empirical coefficients. These vary to such a large extent to meet different conditions of flow and surface that no rational description of the process in general can be drawn.

R. A. Bagnold has carried out a comprehensive investigation on the transport of desert sand by wind. In connection with the initiation of particle-movement, he defines a "static threshold wind," the value of which he found to depend on (a) the former history of the surface, (b) the extent to which sand-removal has collected a protective layer of the biggest grains on the surface, (c) on the surface-turbulence of the wind, and (d) on the length of the exposed surface.

The static-threshold velocity was difficult to determine; however, he found that, once particles began to move, a "dynamic-threshold velocity" lower than the static-threshold velocity would maintain continued particle-movement downwind. He relates this behavior to the action of the particles as projectiles, which upon striking the surface rebound and continue their movement downstream or initiate the movement of one or more particles upon striking the bed. For uniform sand, he found the dynamic-threshold velocity, u_T, in cm per second, to be given by the relation

$$u_T = 0.47\sqrt{(\rho'/\rho)gd}\ \log_{10}(30k'/d) \tag{4}$$

where ρ' is the effective sand-density and k' is the new focus of the velocity-distribution curves obtained from (1) when the flow is carrying particles. For all nearly uniform sands, Bagnold found k' to have roughly the same value, 0.3 cm. For sands of mixed grain-size, according to measurements taken with the natural wind, k' had a value of about one cm. Bagnold's results obtained with uniform quartz sand are reproduced in Figure 10 (note that V_* corresponds to U_*).

According to (1) the dynamic-threshold velocity can also be written in the form

$$u_T = 5.75\ U_*\ \log_{10}(30k'/d) \tag{5}$$

where $U_* = \sqrt{\tau/\rho}$, known as the friction-velocity, z is replaced by k' and k by d/30. Then the friction-velocity required to initiate movement can be solved for from (3) and (4).

$$U_* = (0.47/5.75)\sqrt{(\rho'/\rho)gd} \tag{6}$$

Bagnold gives for his quartz sand $U_* = 120\sqrt{d}$ cm per second, which is plotted in Figure 11 together with his experimental points. For particles smaller than about 0.01 cm, the friction-velocity required to initiate movement was found to increase with decreasing particle-size.

Chepil and Milne found that soil-particles up to 0.8 mm in diameter, making up a smooth, thoroughly dry, pulverized summer fallow, began to move when the wind reached a velocity of 13 to 15 miles per hour at a one-foot height.

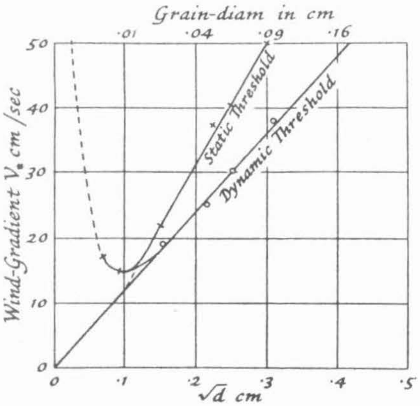

Fig. 11--Friction-velocity required to initiate the movement of sand (According to R. A. Bagnold)

(3) The modes of soil-transport

When a particle is dislodged from the surface by the wind, it moves downstream by sliding, rolling, saltation, or suspension. Bagnold groups the sliding and rolling of particles under the term "surface-creep," which, he states, is brought about by the impact of particles descending from saltation. Saltation is a term used to denote the jumping or bouncing movement of particles within a layer close to the bed. The differences between surface-creep and saltation are gradual, and it is difficult to draw a fixed dividing line between them. The mode of transport a particle will follow will depend on its physical characteristics and on the velocity and turbulent structure of the wind.

In the case of sand-storms, as observed by Bagnold in the Lybian Desert, the height of the visible cloud rarely exceeds five feet, so that, he asserts, all the particles are moving by surface-creep and saltation. Sand-storms of this type occur when the surface is practically free of dust. Measurements in the Egyptian Desert showed that surface-creep amounted to approximately one-fourth the sand-flow in saltation.

Chepil and Milne made measurements of the heights reached by particles in saltation in the open field over loam soil, when the wind-velocity ranged from 15 to 22 miles per hour. Soil-collectors that caught all but some of the finest particles were placed at various heights. These fine particles constituted a small percentage of the transported soil. In Figure 12, the relative quantity of soil blown and relative average diameter of particles are plotted against the height above the surface. Only a small trace of soil was caught at a 38-inch height and 93 per cent of the total soil-movement occurred below a height of 12 inches.

The effect of the turbulent structure of the wind on particles in surface-creep and saltation is not definitely known, although Bagnold believes that turbulence plays a secondary role. Transport by suspension, on the other hand, is directly connected with turbulent fluctuations in the moving air.

Wind-erosion of soil, whose composition varies from fine clay and organic particles to larger sand grains, gives rise to all modes of transport, and fine particles in suspension are lifted to great heights. The appearance of the head of a dust-storm can be observed in Figure 13.

Fig. 12--Approximate curves showing (a) relative quantity of soil blown at various heights over open summer fallow field when wind-speed ranged from 15 to 22 mph at 12-inch height, (b) average diameter in 1/100-mm of soil-particles blown during same period (Measurements of Chepil and Milne)

Von Kármán has made an estimate of the length of time and distance traveled by soil-particles upon being lifted from the surface. Assuming that a particle of mean diameter, d, has the settling velocity, w, given by Stokes' Law

$$w = (2/9)\ (\rho' g d^2/\mu) \tag{7}$$

and that the root-mean square of the height that a particle reaches in an arbitrary time, t, due to turbulence, is given by the turbulent exchange-coefficient, ϵ, according to the formula

$$h = \sqrt{2\epsilon t} \tag{8}$$

then, since h = wt, one obtains

$$t = (2\epsilon/w^2) = 81\epsilon\mu^2/2\rho'^2 g^2 d^4 \tag{9}$$

The range of the particles corresponding to a mean velocity U is given by

$$L = Ut \cong 40\epsilon\mu^2 U/\rho'^2 g^2 d^4 \tag{10}$$

The results in Table 2 correspond to $\epsilon = 10^4$ and 10^5. The value of ϵ for moderately strong winds lies between those limits, except within the first few feet of the ground, where ϵ decreases as the ground is approached.

Table 2

Diameter of particles, mm	Velocity of fall, cm/sec	Time of flight	Range for 15 m/sec wind	Maximum height
0.001	0.00824	9-90 yrs.	$2.5\text{-}25 \times 10^6$ miles	3.8-38 miles
0.01	0.824	8-80 hrs.	250-2,500 miles	200-2,000 feet
0.1	82.4	0.3-3 sec.	150-1,500 feet	2-20 feet

On February 7, 1937, a dust-storm headed northwest from the Texas-Oklahoma panhandle region. Some of the suspended soil--as much as 200 pounds per acre--settled on snow in Iowa, after traveling 500 miles. Analysis of samples taken from the black snow showed that the deposit contained three times as much humus as the best remaining soil in the source-region of the storm.

The presence of transported soil in the air-stream would be expected to alter its usual flow-characteristics, since energy is transmitted from the air to the moving particles. The logarithmic velocity-distribution law is based on the exchange of momentum between neighboring layers of fluid. The solid particles in the flow tend to modify the exchange-process as it occurs in an unladen stream. The alteration in the velocity-distribution by such particles is shown in Figure 10.

Fig. 13--The "black blizzard" or dust-storm of April 14, 1935
(Picture taken southeast of Lamar, Colorado)

(4) The deposition of transported soil

Soil-particles, upon being lifted from the surface, except the very finest dust that becomes a part of the atmosphere, as elaborated by Blacktin, eventually come to rest again when the wind has subsided or when surface-obstructions alter the velocity-distribution and turbulent structure.

Bagnold has described the following three ways in which particles are deposited from drifting sand:

(a) Accretion occurs when the height-velocity gradient diminishes over a flat surface. Particles drop out and the transport of particles by surface-creep and saltation falls off.

(b) Encroachment occurs when the surface has a sudden drop in slope, as, for example, the lee side of a dune or ridge. The heavier particles in surface-creep roll over the crest into a protected region and accumulate.

(c) Sedimentation occurs in regions where the wind-velocity falls below the threshold value.

In the general case of wind-erosion of soil, transported particles are also deposited around obstructions, such as fences, wind-breaks, buildings, etc., which cause localized changes in the wind-structure. The prevention of the accumulation of transported soil in the form of dunes and drifts offers many problems.

(5) Quantity of soil moved by wind

A number of investigators have measured the quantity of soil moved by wind from sand-surfaces and soil-surfaces of different roughness.

In Table 3 is shown the influence of cultural treatment on the amount of soil blown, as obtained by Chepil and Doughty in a laboratory soil-blowing tunnel. The working section of the tunnel was only six feet long, so that field-conditions were not entirely duplicated. The soil used in the experiments was thoroughly air-dried, and the same structure of the soil was maintained throughout the entire experiment. Dry aggregate structure was determined with a set of sieves ranging from 0.15 to 38 mm in diameter opening.

It is interesting to note that a surface of sceptre clay resisted blowing until high speeds were reached. Bagnold found that movement of Portland cement particles, spread out to form a loose flat surface, could not be initiated by a wind-speed of 50 miles per hour at 10-cm height. The explanation for this phenomenon probably lies either in the presence of large forces of cohesion or in the possibility that the particles are completely within the laminar sub-layer.

O'Brien and Rindlaub, in 1936, published, it is believed for the first time, data on the relationship between the amount of sand transported and wind-velocity. Their measurements were made on Clatsop Beach at the mouth of the Columbia River, which consists of sand with a mean diameter varying from 0.0065 to 0.0085 inch. In Figure 14, the sand-drift, G, in pounds per foot width, perpendicular to the wind-direction, per day, is plotted against the velocity, U_5, of

Table 3--The influence of cultural treatment on the amount of soil blown and on the surface-velocity of wind

(Measurements of W. S. Chepil and J. L. Doughty)

Soil-treatment	Amount in grams in five minutes when wind-speed was 22 miles/hour at 12-inch height			
	Hatton fine sandy loam	Haverhill loam	Cypress clay-loam	Sceptre clay
(a) Level, bare surface	110	215	209	xx
(b) Group of 3 ridges, each 1-1/4 inches high, 7 inches wide, placed at right-angles to wind at windward end of 6-foot length of test area	84	71	170	xx
(c) Ridges as in (b) covering the total surface	75	59	87	xx
(d) Level surface as in (a) with half ton per acre of short straw worked into surface	6	34	17	xx
(e) Ridges as in (c) with straw as in (d)	30	13	12	xx

xx The soil did not blow at this speed of wind. At wind-speed 34 miles per hour, 10.2 grams blew off soil treatment (a) but none blew off the other treatments.

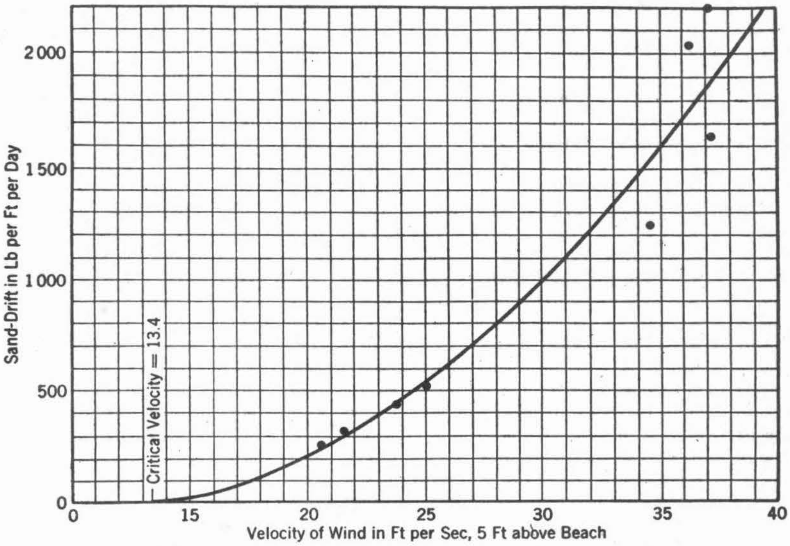

Fig. 14--Relation between wind-velocity and rate of sand-movement (Measurements of O'Brien and Rindlaub)

the wind in feet per second at five feet above the surface. The smooth curve drawn through the points corresponds to

$$G = 0.036\ U_5^3 \tag{11}$$

for values of U_5 greater than 20 feet per second.

In 1938, Bagnold made measurements of the quantity of sand moving during sand-storms in the Egyptian Desert. He found that, for sand having a mean diameter, d, of 0.025 cm, the quantity of sand transported in metric tons per meter width per hour was given by the relation

$$q = 5.2 \times 10^{-4}\ (u - u_T)^3 \tag{12}$$

where u is the wind-velocity in cm per second at one-meter height and u_T = 400 cm per second is the threshold velocity.

(6) Equipment and experimental methods utilizing an artificially created wind

The experimental methods for investigating wind-erosion can be divided into those utilizing the natural wind in the field and those employing a suitably directed artificially produced air-stream. As stated in the introduction, field-studies have certain inherent advantages and disadvantages. Only within the last few years has the application of an artificially created wind been resorted to as an aid in the attack on the wind-erosion problem. For that reason, the possibilities and limitations of the method have not generally been understood and its usefulness exploited. Therefore, it will be the purpose of this section to discuss at some length this new technique.

The design of an installation for producing an air-stream and correctly directing it is greatly facilitated by the large body of knowledge accumulated in connection with experimental aerodynamics, which has gone hand in hand with the development of aeronautics during the present century.

The installation as used in experimental aerodynamics is known as a wind-tunnel. The main components are the fan, working section, and auxiliary sections for straightening the stream and for increasing the efficiency of converting the energy-input to the fan into kinetic energy of the stream in the working section.

The following three types of wind-tunnel, classified according to the action of the air-stream, have been developed:

(a) Working section on the downstream side of the fan
(b) Working section on the upstream or suction side of the fan
(c) Air-stream circulated around a continuous, closed circuit

All three types have been used in the study of wind-erosion, and their component parts will be discussed in connection with the installations that have been constructed. To distinguish the installation from the wind-tunnel, the term soil-blowing tunnel will be used.

Soil-blowing tunnels can be further classified as laboratory and portable. A laboratory soil-blowing tunnel is a permanent unit constructed to give the optimum possible control over the characteristics of the air-stream and test setup. A portable soil-blowing tunnel is a simplified unit of lightweight construction suitable for use in the field. Its component parts can be dismantled in a short time and transported on a trailer.

The laboratory soil-blowing tunnel--In order to simulate full-scale wind-erosion phenomena in a tunnel, it is necessary that the air-stream have a velocity-magnitude and distribution and turbulence-structure similar to the natural wind near the ground, and that the working section be large enough to minimize wall-interference. Velocity-profiles measured in an open-top channel and a rectangular working section are compared with the logarithmic velocity-distribution of the natural wind in Figure 1. The velocity-range of the tunnel should extend from about five miles per hour to a maximum of at least 40 miles per hour, and in this range the speed should be easily controlled. The flow through the working section must be uniform and the turbulence-level with smooth walls should not be in excess of one per cent.

The minimum dimensions of the working section have not yet been definitely determined, especially the length downstream required to simulate certain soil-blowing conditions. According to Bagnold's measurements with uniform sand varying in diameter from 0.18 mm to 0.3 mm at speeds only slightly above the threshold value, an exposed surface 30 feet in length was required before the sand-flow reached an equilibrium value.

The height of the working section, that is, the distance from the soil-bed to the ceiling should be not less than about 18 inches and preferably greater, for particles in saltation have been found to bounce as high as 50 to 100 times the grain-diameter. In determining the width of the working section, it must be noted that measurements should only be carried out in that portion of the working section in which the mean velocity-distribution is two-dimensional. This condition is not met in the boundary-layers adjacent to the side walls. Therefore, the width of the working section must be sufficient to produce a zone of uniform transverse velocity-distribution, whose minimum width equals the desired width of the test setup. Due to the growth of the boundary-layers on the walls, this minimum width is reached some distance downstream from the entrance.

In Figure 15 is shown a vertical elevation of the laboratory soil-blowing tunnel constructed at the California Institute of Technology by the Soil Conservation Service. The tunnel is a modified Eiffel type with the working section on the suction side of the fan. The component parts of the installation, indicated on the Figure, are the honeycomb, entrance, working section, diffuser, settling box, aspiration-chamber, and propeller-motor combination. Recently a diffuser section of sound-proofing material was added on the downstream side of the propeller to reduce the noise-level.

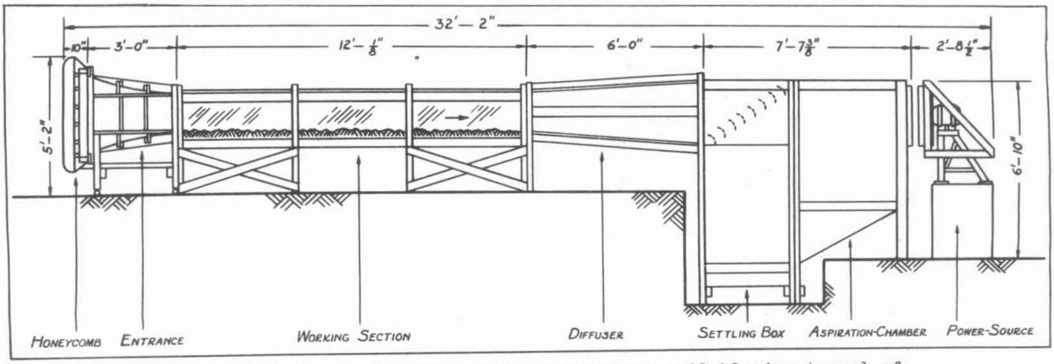

Fig. 15--Vertical elevation of the laboratory soil-blowing tunnel of Soil Conservation Service at California Institute of Technology

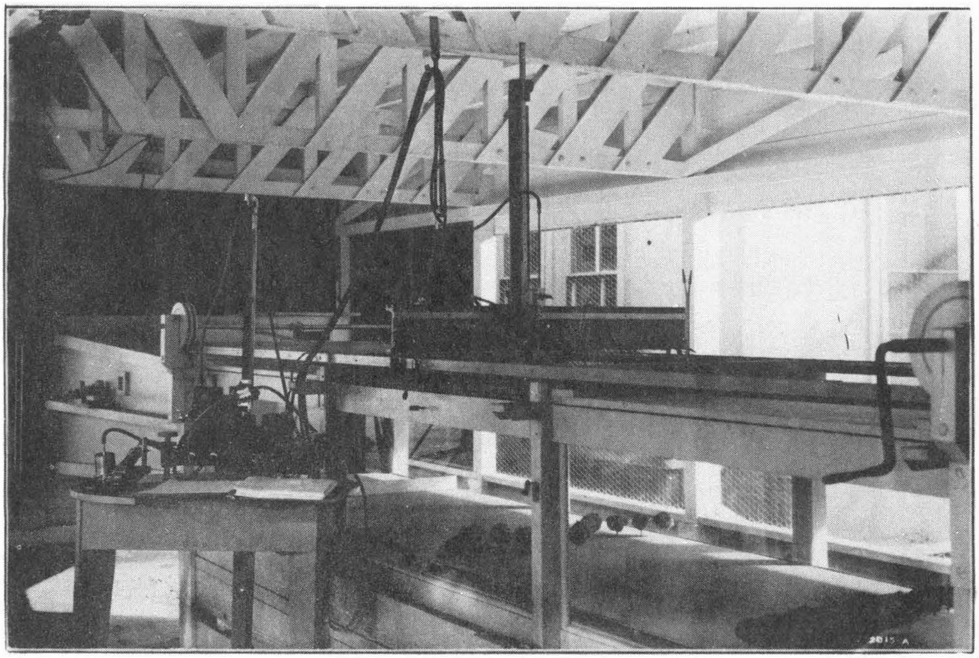

Fig. 16--View of working section and traversing and velocity-measuring instruments

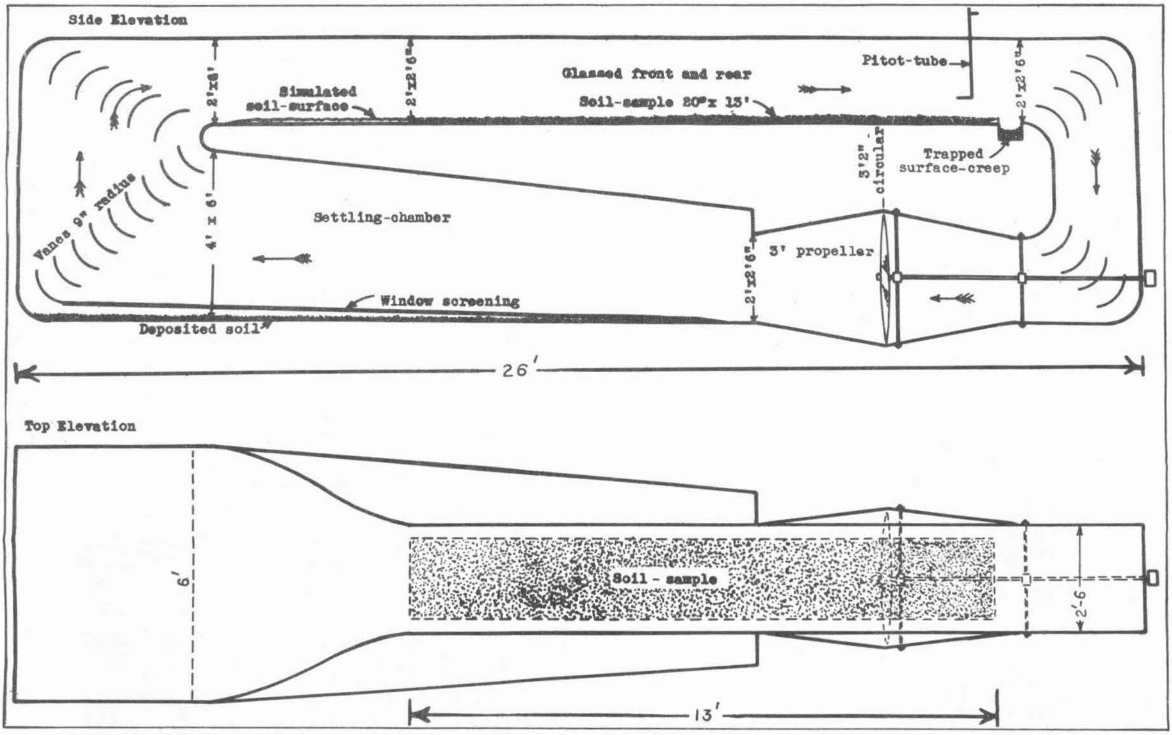

Fig. 17--Vertical elevation and plan of laboratory closed-circuit type soil-blowing tunnel, Soil Research Laboratory, Dominion Experimental Station, Swift Current, Saskatchewan, Canada

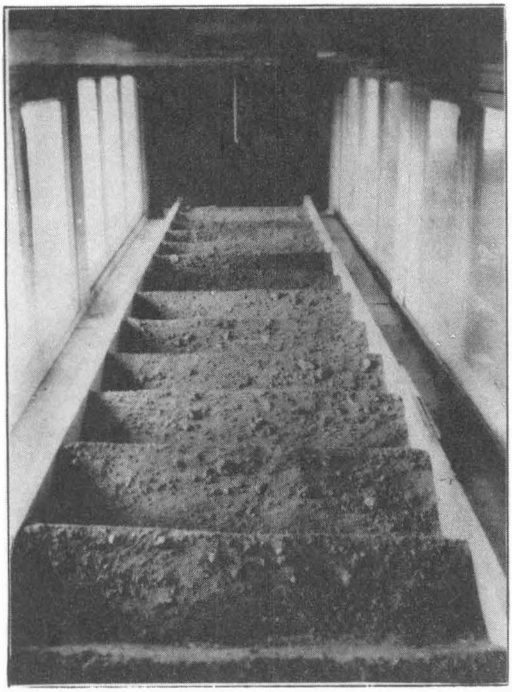

Fig. 18--Interior view of the laboratory soil-blowing tunnel working section

Air enters the working section through a honeycomb, which is built up of about 6,000 pasteboard tubes, each three inches long and one-half inch in diameter, and then passes through a contracting entrance section. Provision is made for the insertion of turbulence grids between the entrance and the working section, for studying the effect of the structure of the air-stream.

The working section, shown in Figure 16, with obstruction models installed, is 2-1/2 feet wide, 1-1/2 feet high, and 12 feet long. Glass side-walls permit visual observations and photographic records to be made during tests. Soil-samples can be spread over the entire floor of the section.

The soil-laden air-stream flows from the working section through a diffuser into a settling box, in which the lower portion of the stream is turned through a 90° angle by vanes and reduced in velocity to remove the greater part of the transported particles. The upper portion of the air-stream enters directly into the aspiration-chamber and is joined by the portion that has been cleaned in the settling box.

The pressure in the aspiration-chamber is reduced by suction from a 29-inch, two-bladed propeller, driven at 3,600 rpm by a seven-HP electric induction motor. The speed of the air-stream in the working section is controlled

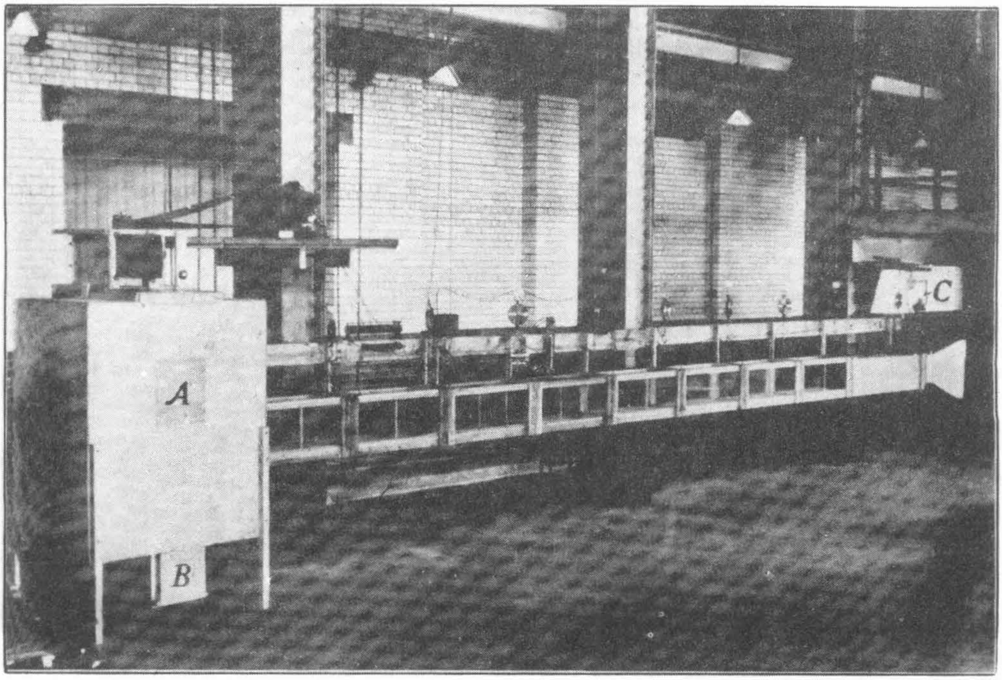

Fig. 19--Laboratory tunnel used by R. A. Bagnold in his studies of transport of desert sand

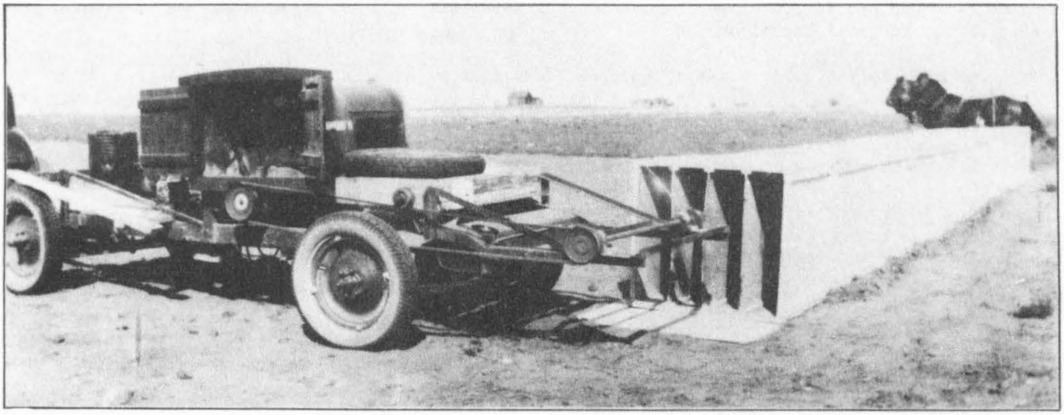

Fig. 20--View of portable soil-blowing tunnel constructed at Soil Research Laboratory, Dominion Experimental Station, Swift Current, Saskatchewan, Canada

by a throttling door between the propeller-tube and the aspiration-chamber. A speed range of 5 to 43 miles per hour can be obtained.

A laboratory soil-blowing tunnel of closed-circuit type is in use in the Soil Research Laboratory, Dominion Experimental Station, Swift Current, Saskatchewan. In Figure 17, an elevation and plan of the tunnel is shown. The working section, shown in Figure 18, with a soil-sample ready for testing, is 2-1/2 feet wide, 2 feet high, and 13 feet long. Wind-speeds up to 35 miles per hour can be obtained. Investigations carried out in the tunnel have shown that soil-blowing as encountered in the field can be satisfactorily simulated.

Bagnold, in carrying out his studies on the transport of desert sand by wind, used a tunnel with the working section on the suction side of the fan (see Fig. 19). This section was one foot square and 30 feet long. The length of the tunnel was constructed of ten units, joined together and supported at the joints by spring-balances. The rates of sand-removal and deposition in any section could, therefore, be measured by direct weighing. A maximum speed of approximately 50 miles per hour was made available.

The portable soil-blowing tunnel--Since soil-factors vary to such a great degree between areas in the wind-erosion regions, it has been found desirable to develop a wind-machine for use in the field. By the aid of this device, the fundamental relations discovered in the laboratory

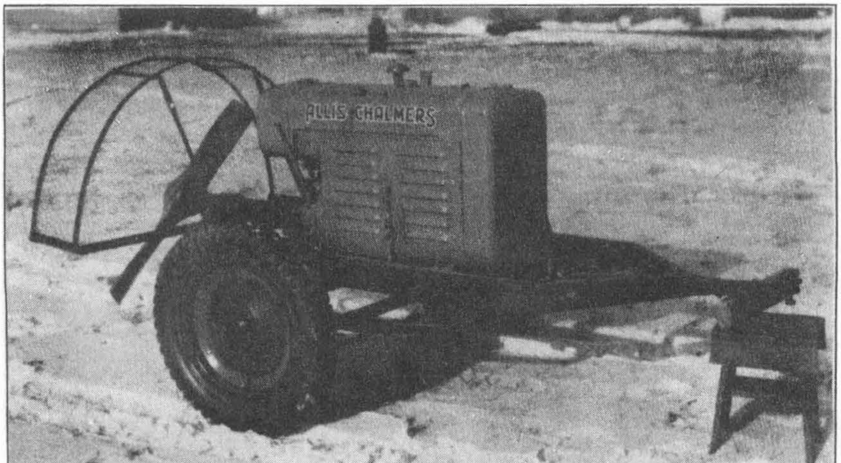

Fig. 21--View of power-unit and propeller used in the portable soil-blowing tunnel of Soil Conservation Service, College Station, Brookings, South Dakota

tunnel for the prediction of the behavior of soil-surfaces exposed to wind can be correlated with particular soil-conditions.

Portable soil-blowing tunnels, thus far constructed, have been greatly simplified in design, at times to such a degree that the value of the results obtained have been appreciably reduced. The most convenient type of tunnel for this application is one with the working section on the downstream side of the fan, for, with this type, the wearing of the fan by particles in the air-stream need not be contended with.

To minimize the weight of the unit for transportation, only a rudimentary honeycomb is used and the converging entrance section has been eliminated. For that reason the rotation of the slip-stream has not been completely eliminated and both the vertical and transverse velocity-distributions have irregular characteristics.

It is believed that a lightweight unit can be built without sacrificing the advantages of a controlled air-stream, limited only by the fluctuations induced by the variations in velocity of the natural wind.

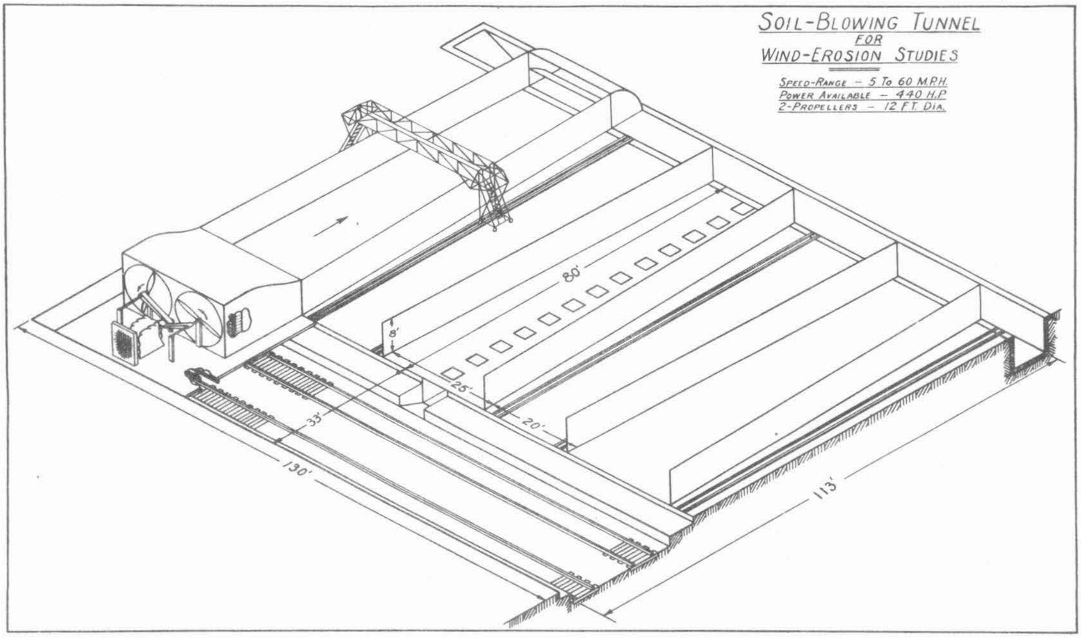

Fig. 22--Layout showing general view of proposed semi-permanent soil-blowing tunnel

The portable soil-blowing tunnel in Figure 20 has been constructed at the Soil Research Laboratory, Dominion Experiment Station, Swift Current, Saskatchewan. The air-stream is created by a 42-inch propeller driven by an automobile engine. The stream enters the working section through a section four feet long, provided with three vertical baffle-boards. The working section is three feet wide, 3-1/2 feet high, and 44 feet long.

A similar portable tunnel has been designed and constructed by C. C. Joy of the Soil Conservation Service at College Station, Brookings, South Dakota. The power-unit used is shown in Figure 21. A second portable unit is being constructed by the Soil Conservation Service Station at Amarillo, Texas, under the direction of Dr. C. J. Whitfield.

A semi-permanent type of soil-blowing tunnel (Fig. 22) for large-scale investigations has been proposed by Dr. Theodor von Kármán and the present author. The installation is designed to enable shipment of the parts from one soil-blowing area to another.

Instruments--The study of the wind-erosion process has brought forth the need of specialized techniques and instruments for determining the significant quantities involved. Experiments involving transport of soil near the surface must be carried out rapidly, for the surface is continually undergoing change and, furthermore, the surface is sensitive to the presence of any device that in any way alters the normal flow-pattern of the air-stream.

In an unladen air-stream, the mean-velocity distribution and the turbulent structure can be determined with instruments developed in experimental aerodynamics, such as the pitot-static tube for the mean speed, and the hot-wire anemometer for the turbulent fluctuations. The feasibility of measuring the turbulence-structure in a laden stream by means of a hot wire has not been decided definitely since, at least in the case of sand-particles, the fine wire is broken by the impacts of the grains.

One of the important phases of wind-erosion for which experimental data should be obtained is the distribution of burden carried by the air-stream above the surface. As far as is known, no accurate method of measuring the density of this flow has been worked out. Soil-traps have been found not very satisfactory, since they catch practically no suspended fine particles and they disturb the flow appreciably. The use of a photoelectric cell to measure the absorption of light in a light-beam, and the pumping of air through a sampling tube at the same rate prevailing at the measuring point in the laden air-stream are two methods that have been proposed for trial.

The wind-erosion problem has not yet required any new techniques or instruments for determining the physical characteristics of soils, or the aerodynamic properties of obstacles.

(6) Windbreak experiments in a wind-tunnel

The usefulness of obstacles of various kinds in combating wind-erosion has long been appreciated. Recent dust-storms on the Great Plains originated because the surface, once overgrown with a protective vegetation, is now largely denuded. When land in this region is clean-tilled or overgrazed and the original protective layer destroyed, the ingenuity of man is required to replace it by equally efficient guardians.

On the basis of the discussion in the preceding sections, it can be concluded that if soil subject to wind-erosion must be exposed to prevent the initiation of soil-movement, the velocity near the exposed surface should be reduced to a minimum possible without increasing the turbulence-level of the air-stream. To reduce the velocity of the wind near the ground the kinetic energy in the moving air must be dissipated or the wind deflected upward.

In the practical problem of wind-erosion control over large areas, some of the most suitable obstacles are to be found in tree and hedge windbreaks and close-growing tall grass-barrier strips. In laying out windbreaks, information is needed on the arrangement of planting that will protect the largest possible area. A number of field-investigations have been conducted in this and other countries to determine the above characteristics and also the effect on the productivity of land.

This section will contain some unpublished results of wind-tunnel tests on windbreaks, carried out at the Guggenheim Aeronautical Laboratory of the California Institute of Technology by J. S. Atsumi in 1936 upon the suggestion of Dr. Th. von Kármán.

The experiments were made in a suction-type wind-tunnel (Fig. 23), with a working section 30 inches deep and 9-9/16 inches wide, at wind speeds of 65 miles per hour. Model trees, one inch in height, made of 3/4-inch cotton balls, through which nails were stuck leaving 1/4 inch between the tunnel wall and the cotton balls were used. Various arrangements tested are shown in Figure 24. Identical arrangements of the model trees were installed on both walls of the working section, in order to assure a similar type of air-flow over both walls.

The Reynolds Number of the experiment corresponds to a value of 5×10^4; whereas, in full scale for 30-foot trees and a wind-speed of 30 miles per hour, a value of 8.5×10^6 is obtained. Studies of the drag of spheres with a rough surface show, however, that the drag-coefficient practically is independent of the Reynolds Number; therefore, the model tests should not be greatly in error.

Velocity-surveys were made with a pitot-static tube in the center of the working section, from midstream to within 1/16 inch of the wall, at various stations downstream.

In Figure 25 are plotted velocity-distributions (u_w/u versus z/H) at a station four times the height, H, of a tree downstream of the rearmost trees in the arrangement. The pitot-static

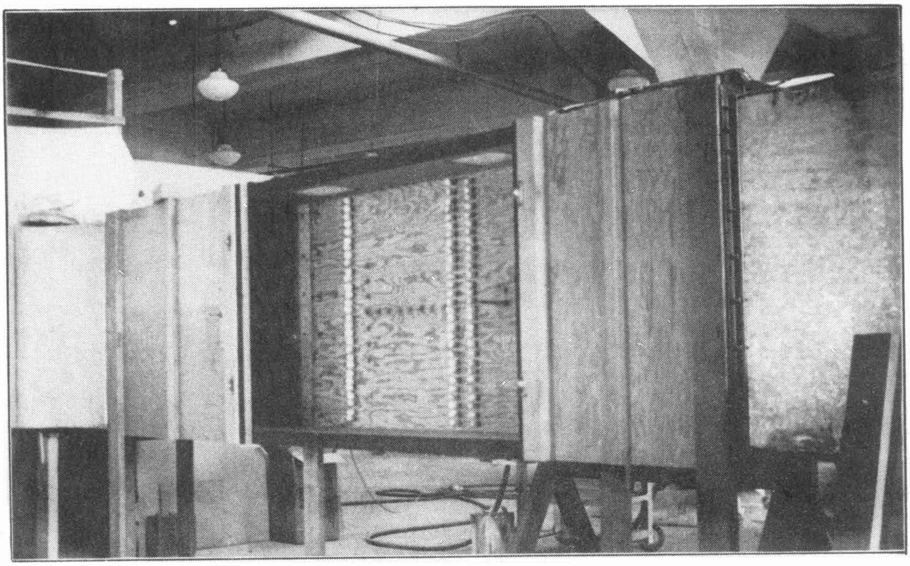

Fig. 23--View of working section with windbreak arrangement installed on one wall

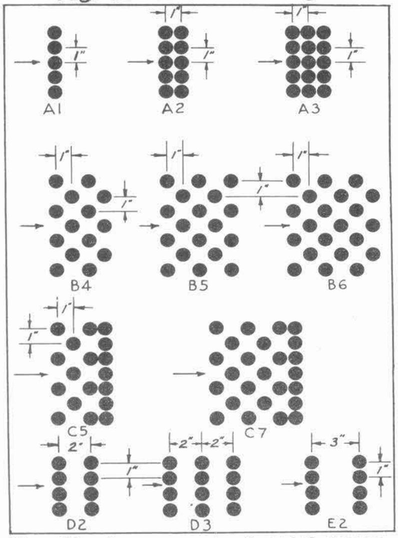

Fig. 24--Arrangement of model trees tested in windbreak experiments

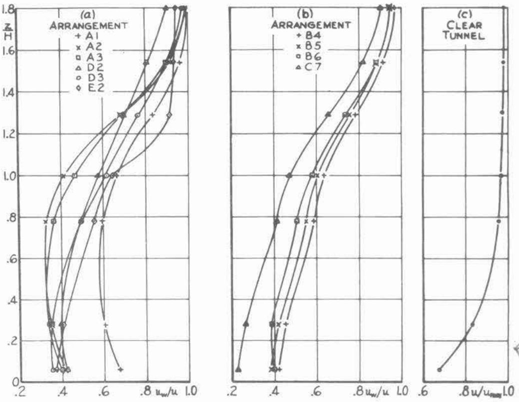

Fig. 26--Velocity-contour map in a vertical plane downstream of arrangement A-2

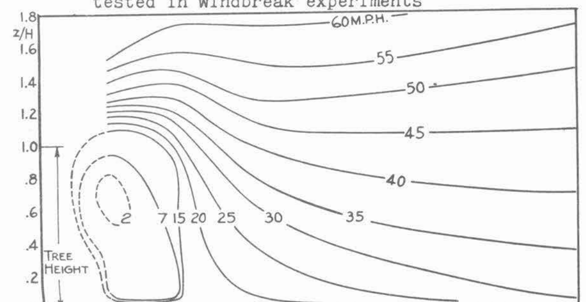

Fig. 25--Velocity-distribution curves, measured at X = 4H, for various arrangements are shown in (a) and (b) and in a clear tunnel in (c) [u_{max} = 65.5 mph]

Table 4

Arrangement	$(1 - u_w/u) \times 100$ at $z = H/5, \mathcal{X} = 4H$	No. of trees per 4H width	Shielding effectiveness per tree
A-1	37	4	9.3
A-2	63	8	7.9
D-2	60	8	7.5
E-2	60	8	7.5
B-4	56	8	7.0
B-5	60	10	6.0
D-3	65	12	5.4
C-7	75	14	5.4
A-3	64	12	5.3
B-6	62	12	5.2

tube was located in the gap between two trees in the last row. In Figures 25 and 26, the following notation has been used: u = local mean air-speed in a clear tunnel; u_w = local mean air-speed at corresponding points, with windbreak arrangement installed; u_{max} = maximum mean air-speed at center of the working section = 65.5 miles per hour; $\mathcal{X}$ = distance downstream from rear row of windbreak; z = distance above surface; H = height of tree.

To compare the shielding effectiveness of different arrangements, the values for the wind-velocity reduction in per cent for $z = (1/5)H$ and $\mathcal{X} = 4H$ were chosen from Figure 25, and these values were divided by the number of trees per unit-length of the windbreak. Shielding-effectiveness values per tree for the various arrangements are shown in Table 4. It is seen from Table 4 that arrangement A-1 gave the greatest shielding effectiveness per tree. However, the windbreak used in this arrangement reduced the velocity the least at a station a distance equal to 4H. The windbreak with arrangement A-2 gave great shielding per tree as well as per windbreak.

Since arrangements A-1, A-2, and D-2 gave the highest shielding-effectiveness values, wind-velocity surveys were made for these arrangements at stations downstream as far as 16 times the height of a tree. A velocity-contour map in the vertical plane downstream of arrangement A-2 is drawn in Figure 26. (The velocity-contours should not be confused with stream-lines.)

The decrease of wind-velocity, due to the various arrangements, became almost the same when the distance downstream exceeded 6H. If a 50 per cent decrease in velocity of the free wind is chosen arbitrarily as the maximum required at $z = (1/5)H$, then a windbreak of arrangement A-2 must be followed by another similar windbreak at a distance of about 12H to protect the soil-surface beyond that point.

A closer study of the velocity-contours plotted in Figure 26 shows that actually, as the ground was approached below (1/10)H immediately to the lee of the trees, the wind-speed again increased, because the space between the trees permitted excessive wind-penetration. Such penetration can be reduced in an actual windbreak by planting bushes or grass between the trees. It should not be concluded, however, that it is desirable to eliminate penetration. On the contrary, preliminary model-tests demonstrated the superiority of tree windbreaks to solid fences of the same heights.

Conclusion

In this survey, an attempt has been made to review the present status of the dynamics of wind-erosion from the viewpoint of the soil conservationist, in whose hands lies the responsibility for preventing the destructive effects of the process. The solution of the problem is dependent on a program that correctly balances the progress made in theoretical studies and laboratory investigations of the underlying principles of wind-erosion with the development of practical methods incorporating the adjustments required to meet the aspects of the problem as they are encountered in particular situations under actual conditions in the field.

There is available only a rudimentary understanding of the basic mechanisms that need to be investigated and interpreted before a generally useful body of theory can be developed for predicting the behavior of soil-surfaces exposed to wind. Studies will require a careful breakdown of the many factors that play a part into significant groupings before their effects can be determined. Furthermore, in these studies it is of great importance that all the variables entering into the experiments be known and controlled.

The most satisfactory way of meeting these conditions appears to be through the application of an artificially created air-stream in a soil-blowing tunnel.

The design-criteria for laboratory tunnels suitable for blowing soil and for model-studies have not been definitely decided, for example, the length of soil-surface that must be exposed and the height of the working-section ceiling above the surface required to simulate actual conditions. Tunnels so far constructed are, however, satisfactory for qualitative evaluations.

The development of instruments for measuring wind-structure and the distribution of carried particles needs to be accelerated. The technique for determining the turbulent characteristics of an unladen air-stream has been worked out, but the equipment is available only in a few aeronautical laboratories. A device for measuring the density of a soil-laden air-stream, within layers very close to the surface, is needed in conjunction with analyses of the formation of surface-markings, such as ripples.

The advantages of laboratory tunnel investigations of models of obstructions and surface-formations are only beginning to be realized. For example, the cumulative effect of a series of windbreaks, spaced at different distances downstream, the effect of departing from straight-line planting of windbreaks, and the most efficient method of utilizing the natural wind to disperse sand-dunes are typical problems that lend themselves to model-studies.

The mechanism underlying the formation of dunes has long been sought. Bagnold found that small-scale experiments in his tunnel with a sand-surface of varying texture gave results that might possibly explain dune-formations. This work needs extension.

Qualitative interpretations of the results obtained with models can easily be drawn; however, quantitative evaluations are awaiting the establishment of similarity laws for air-flows carrying granular material and for models mounted within the boundary-layers of a flow over a surface.

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